Rigidizing Deployable Optical Structures in the μ-Strain Regime*

An Emerging Idea Where Adhesive and Adhesive-Augmented Latches May :

- **Minimize Multiple Positional Equilibrium States**
- **Reduce μ-Structural Behavior Uncertainties**
- **Enhance Latching Robustness**

Objective is to Make Deployable Optical Telescopes Behave as if they Were Jointless and Carefully Assembled at the Factory

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Rigidizing Deployable Optical Telescopes in the Micro-Strain Regime

Erecting or deploying a 10 to 20m-class optical telescope from a "kit of parts" that are folded or otherwise disassembled to fit within 4 to 5m diameter fairing limited payload volume challenges designers to find ways to lock them together without introducing unacceptable levels of flexibility or positional instability. This paper describes an emerging concept where dry film, heat activated adhesives or two-part epoxies are used to make these connections, replacing and/or augmenting mechanical latches or other mechanism-related approaches. Some suggested experiments for characterizing these joints in the small-strain or micro-dynamics regime is presented.

Please note the title, "Rigidizing Deployable Optical Structures" isn't intended to imply that these structures will be any stiffer than they would be if they weren't deployable. Rather, it means that they won't be any less rigid than they would be if they were carefully assembled in the factory. Specifically the joints and latches needed to implement the deployment and lock-up functions, and the local structure to which they are attached, must not add flexibility to perhaps an already very flexible structure. Arguably more important, 'rigidizing' also means that any incipient looseness or load dependent stiffness characteristics associated with vibration and any non-repeatable force-deflection characteristics of the joint will be eliminated or minimized in the critically important (to precision optical systems) micro-to-nano strain regime. In other words, the goal is to make the design behave as the designer intended, like a continuous strain flow path.

This paper is presented as a set of briefing charts which are largely self-explanatory. We begin with a definition of some of the issues that tend to set precision optical structures apart from ordinary spacecraft structures, particularly in the realm of micro-mechanics and micro-dynamics. A brief summary of those attributes which are desireable, if not mandatory, to make the deployed telescope behave as if it were carefully assembled in the factory is presented. We then describe several different classes of joints that might be employed in the design of a a large deployable optical telescope and how they approach these aforementioned objectives. One conclusion reached is that if the telescope was a factory assembled monolith, its construction might very well employ adhesive bonded continuous joints as opposed to a pinned and bolted design or an integrally machined jpintless unit. These approaches are perhaps best exemplified by the 5m long x 2.8m Hubble Secondary Mirror Truss and the all-beryllium ITTT/SIRTFcryogenic telescope.

So then, the question was whether we could devise a way to "glue" the deployed components together in space and achieve what we might be able to achieve in the factory. Several approaches to accomplishing this for different classes of joints are illustrated here and it appears that this idea, to 1'st order, merits further study and evaluation. We show that the bond-line proportions for a 'glued in space' joint will not degrade stiffness. Loads transfer is accomplished over a broader area than is practical with mechanical joints, thus precluding local flexibility in the surrounding local structural areas. We also show that the sometimes very tight tolerances, required to ensure that a 'system' of latches separated by possibly meters of structural path length do indeed fully engage, are relaxed with this approach. A concept for storing and then applying adhesives to effect a bonded connection in space is described.

Finally some fundamental experiments to help mature this idea from its current paper stage to hardware demonstrations are presented, including testing in the micro-to nano-strain regime.

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Outline

Problems with Latches

HST, a Glued-Together Structure

Tower Telescopes

Deployable Tower

Why Bonded Joints

How They Work

Some Key Experiments to be Done

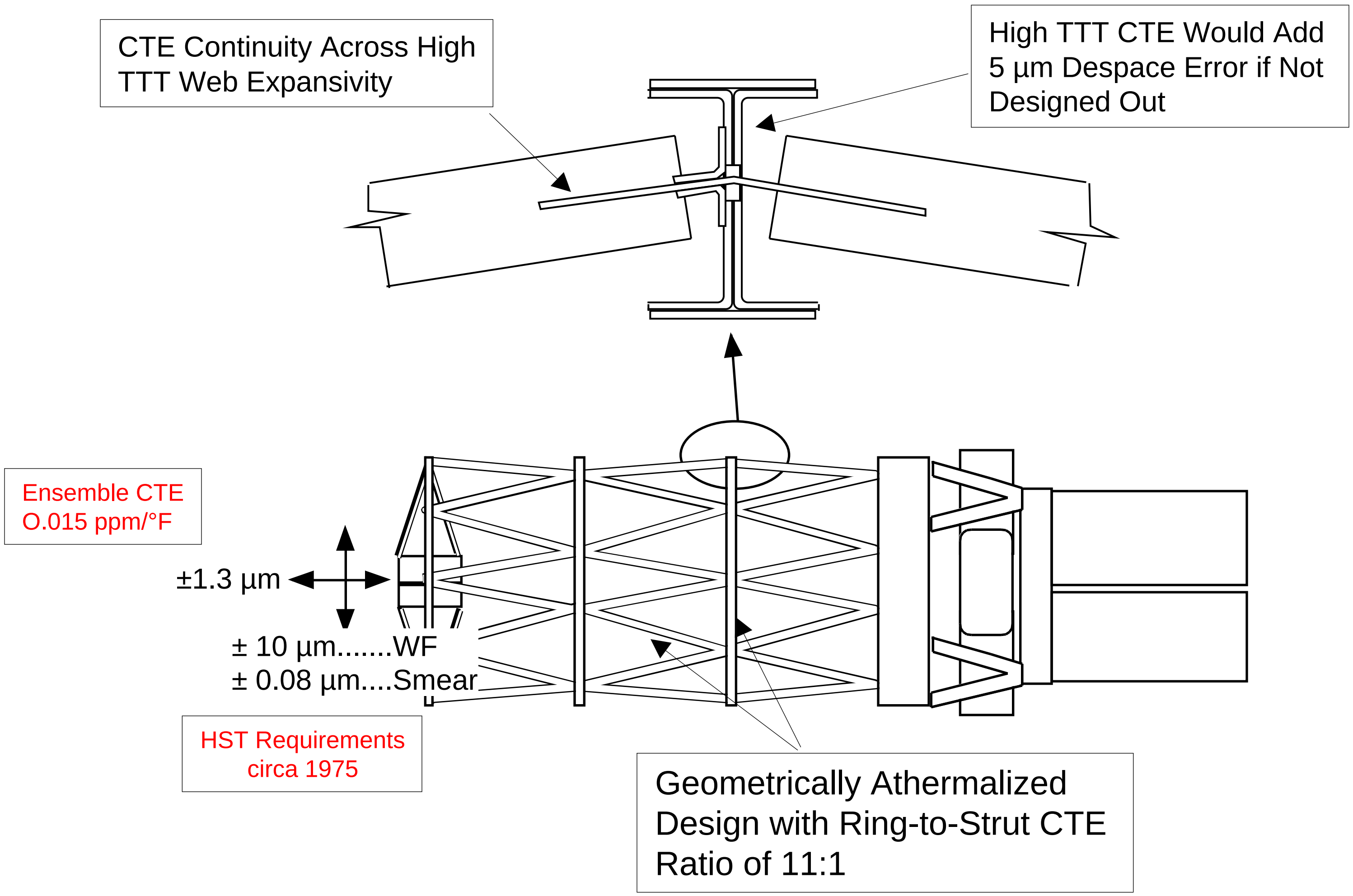
Potential Problems with Deployment Latches

They:

- can shift position
- can add more flexibility to potentially already very flexible systems
- have uncertain and sometimes non-repeatable micro-vibration transmission characteristics
- may exhibit non-recoverable deformations and multiple small-strain equilibrium states
- may have non-linear and non-repeatable small-strain stiffness and damping characteristics
- …. and thereby complicate any feed-back control systems
- are hard to account for analytically at the overall OTA level
- might not work!
- and in general, are poor substitutes for careful factory assembly

HST's Bonded Joints

Achieved Highly Predictable and Repeatable Performance



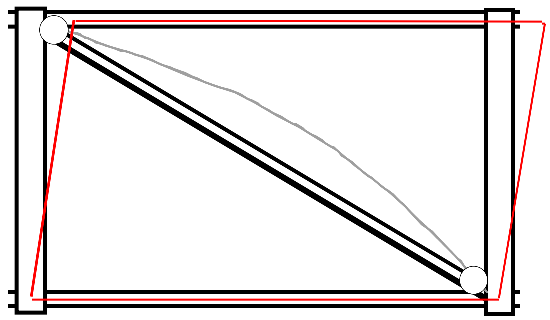
48 Struts and Four Rings with a Total of 8 Mechanical Joints, <u>Assembled with Gravity Off-loaders to</u> Minimize Parts Fit-up Internal Strains

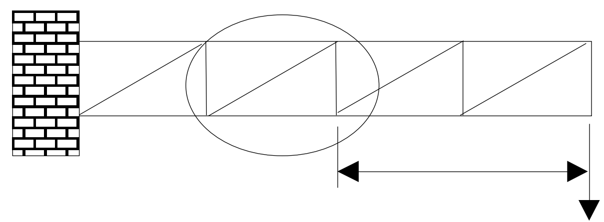
Why Strain-Free Assembly; A Simplified Example

0.1mm Intererence-Fit of 1700mm Diagonal Puts Strut into Near-Buckling Limit

If Operational Thermal or Dynamic Loads or Whatever Cause it to Buckle

Slope Change is 0.00017 radians or 175 µm per meter of Structural Length





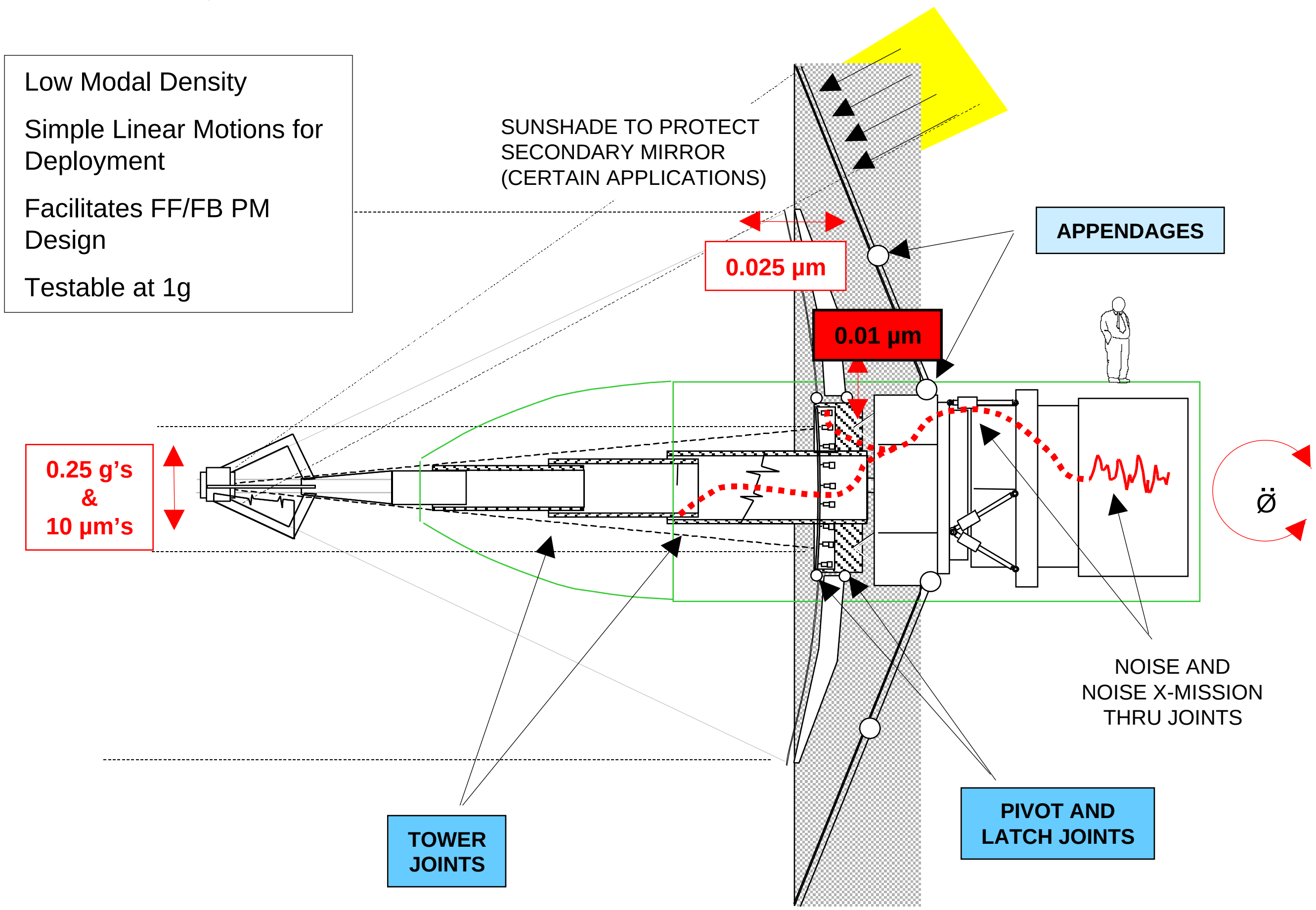
Structural Parameters

a	30	inches
b	60	inches
L	67.0820393	inches
MoE	1.20E+07	psi
CTE	5.00E-08	per °F
OD	0.5	inches
t	0.02	inches
MoI	0.0009825	in^4
A	0.0314	in^2
P'	2.58E+01	lbs

Ø	sinØ	sin^2 Ø	cosØ	cos^2 Ø	L'	Delta L	Strain	Stress	Load
0.0025	4.3611E-05	1.90193E-09	1	1	67.0832095	0.00117015	1.74435E-05	2.09E+02	6.57E+00
0.005	8.7222E-05	7.60772E-09	1	0.99999999	67.0843795	0.00234017	3.48852E-05	4.19E+02	1.31E+01
0.0075	0.00013083	1.71174E-08	0.99999999	0.99999998	67.0855494	0.00351008	5.23251E-05	6.28E+02	1.97E+01
0.01	0.00017444	3.04309E-08	0.99999998	0.99999997	67.0867192	0.00467986	6.97632E-05	8.37E+02	2.63E+01
0.0125	0.00021806	4.75482E-08	0.99999998	0.99999995	67.0878888	0.00584951	8.71994E-05	1.05E+03	3.29E+01
0.015	0.00026167	6.84694E-08	0.99999997	0.99999993	67.0890584	0.00701905	0.000104634	1.26E+03	3.94E+01
0.0175	0.00030528	9.31945E-08	0.99999995	0.99999991	67.0902278	0.00818846	0.000122066	1.46E+03	4.60E+01
0.02	0.00034889	1.21723E-07	0.99999994	0.99999988	67.0913971	0.00935775	0.000139497	1.67E+03	5.26E+01
0.0225	0.0003925	1.54056E-07	0.99999992	0.99999985	67.0925662	0.01052692	0.000156926	1.88E+03	5.91E+01
0.025	0.00043611	1.90193E-07	0.9999999	0.99999981	67.0937353	0.01169597	0.000174353	2.09E+03	6.57E+01

A 10m Generic Deployable Telescope with Three Classes of Joints

- 10 µm and 10 nm Positional Stability for SM and PM Respectively
- Can Mechanical Latches be Replaced with In-Flight Bonded Joints?
- Maybe!



Three Classes of Joints….cont'd

- **Fastening a Secondary Mirror Support Tower Together**
  - Distributed Structure, Therefore Continuous Joints Desirable
    - re. Structural Efficiency
  - Subject to Significant Lateral Loads During Repointing
    - Can be a Major Image Jitter and LoS Error Source
      - FSM and/or Active Damping
  - As Little as 10 µm Hysteresis Can Exceed WF Requirement
    - Rapid Error Sensing & Correction Req'd, Some Applications
  - An Old Problem Has Gotten Tougher

- **Rotating and Locking Deployable Primary Mirror Segments in Place**
  - Jitter Limits ≈ 0.015 λ rms WF or 0.12 λ P-P Tip Displacement
    - Much Tighter than SM Static or Dynamic Tolerances
    - Equivalent to 0.02 λ or 10 nm motion of latch or pivot region motion
    - Not Correctable with FSM's or Similar Methods
  - A New and Tough Problem

- **Folding Out and Locking Appendage Support Struts**
  - Looseness to be Avoided re. CS Feedback

Where the 10nm Came From

For Diffraction Limited Performance at 0.6 µm
WFE ≤ 0. 04µm rms

PM
0.03 µm rms

Everything Else
0.025 µm rms

Petal Figure	0.02
Petal RoC Mismatch	0.015
Petal Tilt	0.015 µm rms

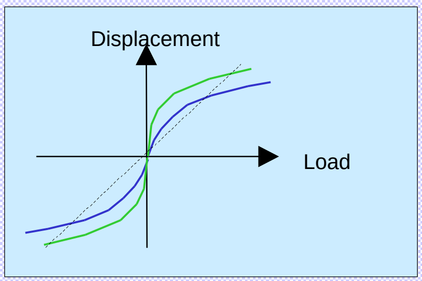
0.05 µm P-V Approximately in WF Space

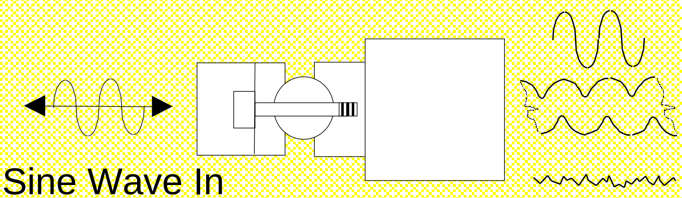
0.025 µm P-V in Surface Space

About 10 nm at the Latches

SOA
Space Optics Applications

Some Micro-Mechanical Concerns with Mechanical Latches, When 0.01 μm is Important





Sine Wave In

Sine Wave Out

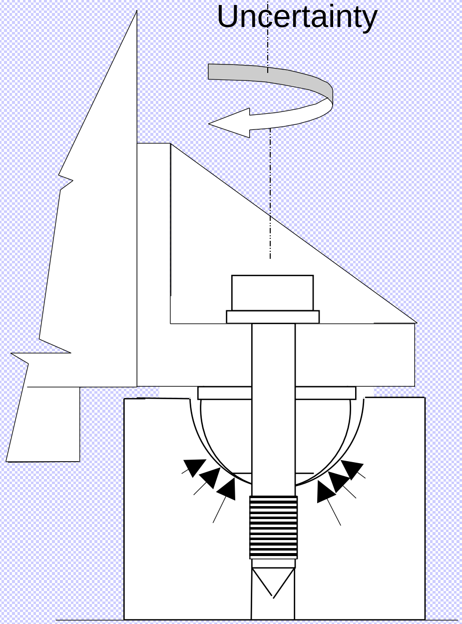
Poorly Modulated SW

Noise

Not Like a Continuous
Mono-Material One-Piece Load-Path

Where iDoes Belief in 'NASTRAN' Become Questionable?

Installation Force
Uncertainty



Load-Variable
Contact Area,
i.e. Stiffness

Indeterminate or
Unstable Geometry
or Both

Indeterminate
Entrapped Strain Energy

Indeterminate
Friction

Not Like a Properly Designed
and Installed Bolted Joint
or a Bonded or Integral Assembly

The Hubble Instrument Registration Latches, Designed for ±435 μm Image Space Applications, are Not nm-Class PM Segment Latching Devices

In View of the Foregoing, Here Are

Some Attributes of a Desirable 0-g Deployable Joint

- **Assured Latching and Deterministic Positional Accuracy**
  - In the Presence of Distortions and Other Non-Ideal Conditions
- **Predictable and Repeatable μ-Dynamics and μ-Mechanical Behavior**
  - Smooth Strain Flow and Structural Continuity
  - Repeatable Small-Strain Elastic Properties
  - Minimal Entrapped Strain Energy
- **CTE Continuity**
  - A 'Sometimes' Issue with In-Loadpath Mechanical Devices
- **Testable at 1-g**
  - With a Minimum Amount of Off-Loading STE
  - No differences Between 1g and 0-g Dynamic Characteristics
- **Other:**
  - Harness and Cabling Compatibility
  - Weight
  - Number of Parts
  - Temperature
  - Launch Survivability where Applicable
  - etc.

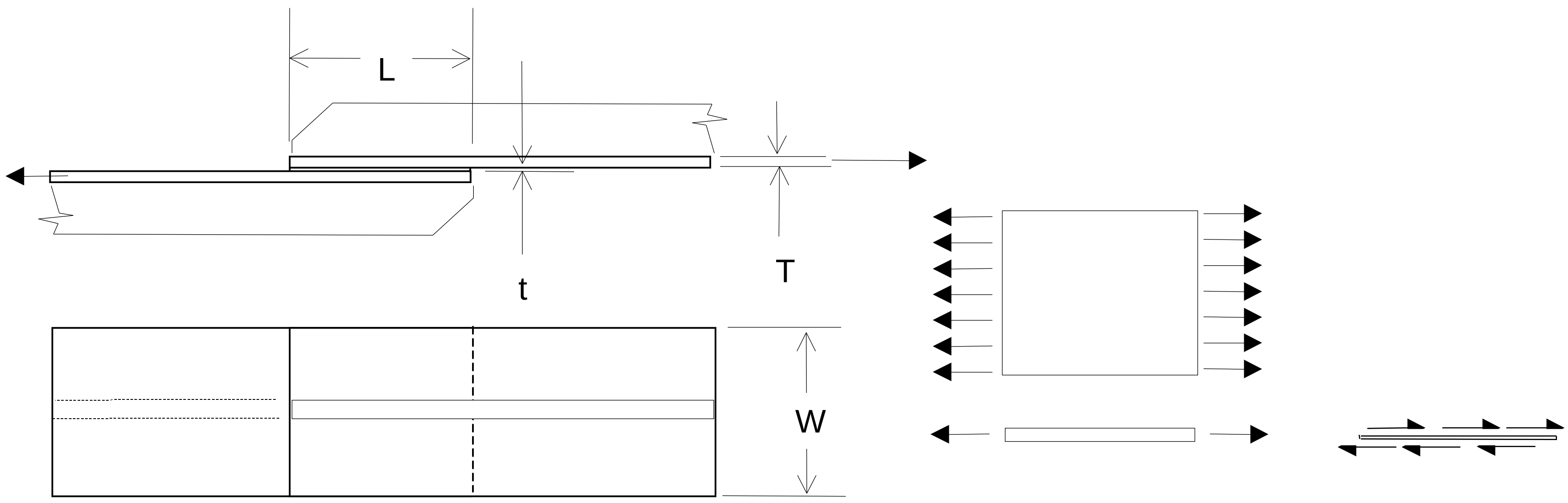
Which Leads Us to
<u>Bonded Deployable Connections</u>,
An Emerging Concept

- For Primary Loadpaths Where:
  - adequate shear area is available
  - loads are relatively low
  - configurations are compatible with good bonding geometry
- For Parallel or Secondary Loadpaths Where:
  - bondline is primarily to eliminate potential looseness
  - geometry is not well suited to good bonding practice
    - partial loss of bondline integrity is tolerable
    - rigidizing a journal pivot, for example
- Provides Solutions to Some Applications, Not All

Adhesive Options Under Consideration

Two-Part Epoxies	Gap Filler for Journal Pivots Plus Other …...
Heat-Activated Dry Film Adhesives	Lap Shear Applications
Solvent-Activated Dry Adhesives	aka postage stamps & PVC pipes….Contamination
Pressure-Activated Tacky Adhesives	Handling and Application Problems…aka duct tape
Single Part Adhesives	B-Staged Epoxy, for example…..Shelf-Life Limited

Bondline Itself Should Not Add Flexibility…..



Kb = WLG / t

Km = WTE / L

For Equal Stiffness,
t ≤ L^2 G / E T

Adhesive stiffness equal to or greater than the material it replaces, if proportioned properly

L = 1in
G adhesive = 0.1Mpsi
E adherend = 12 Mpsi
T = 0.1 in”

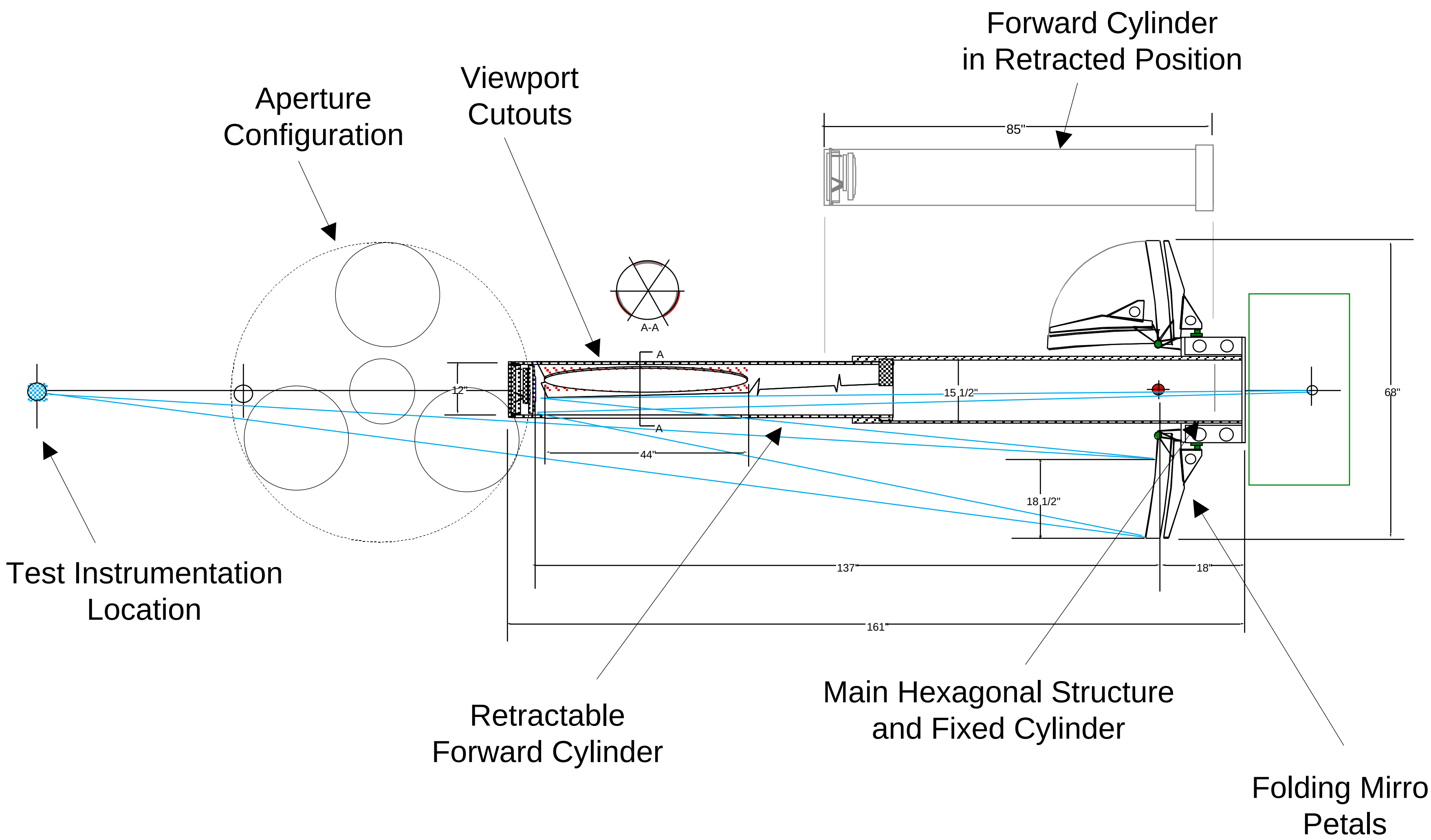
t ≤ 0.08 in.

A Specific Design Concept

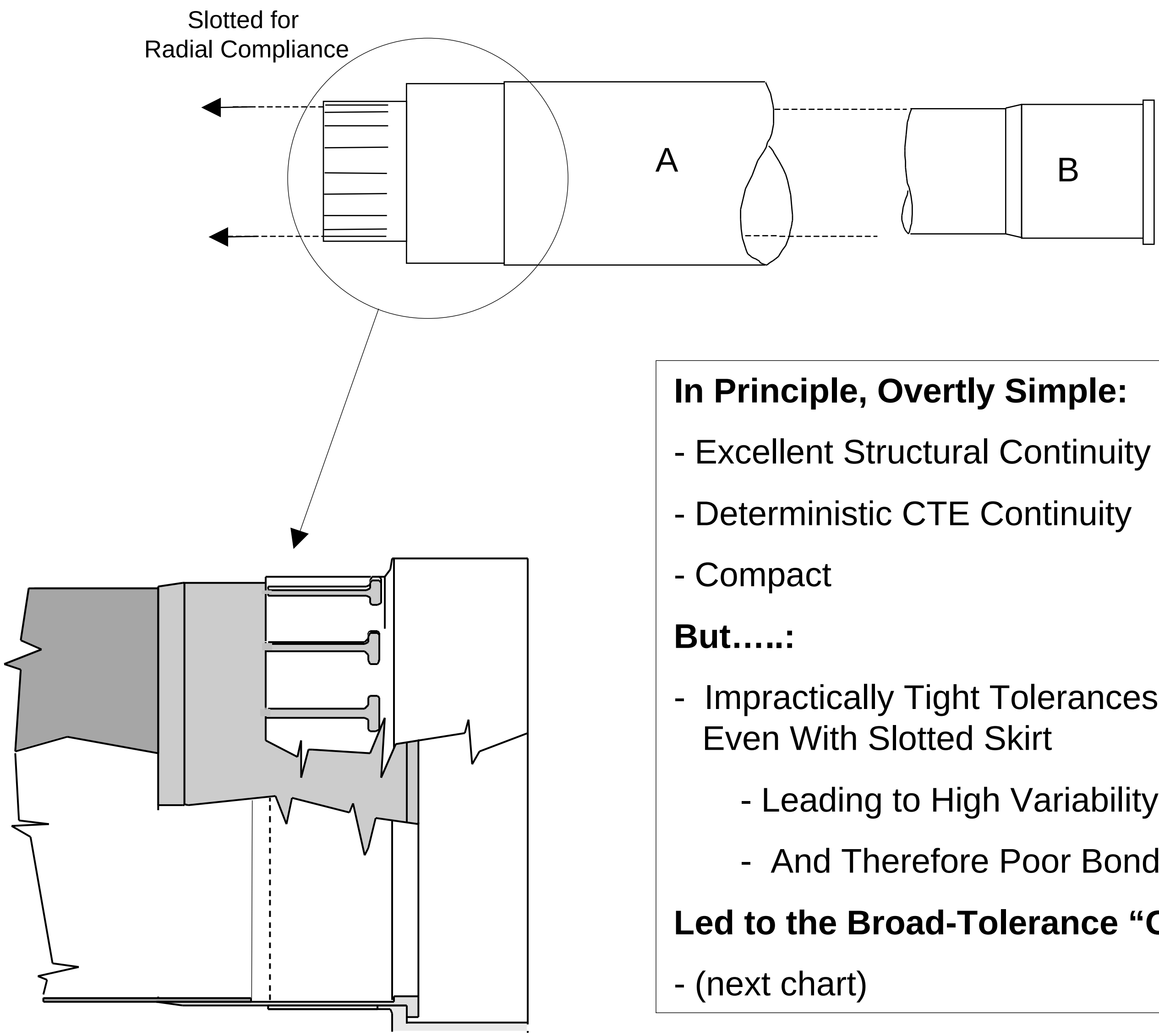
for a

High Slew-Rate Application

PDOS, an Early Reference Concept



Initial Concept for Sleeve Joint



In Principle, Overtly Simple:

- Excellent Structural Continuity

- Deterministic CTE Continuity

- Compact

But…..:

- Impractically Tight Tolerances for Large Diameters Even With Slotted Skirt

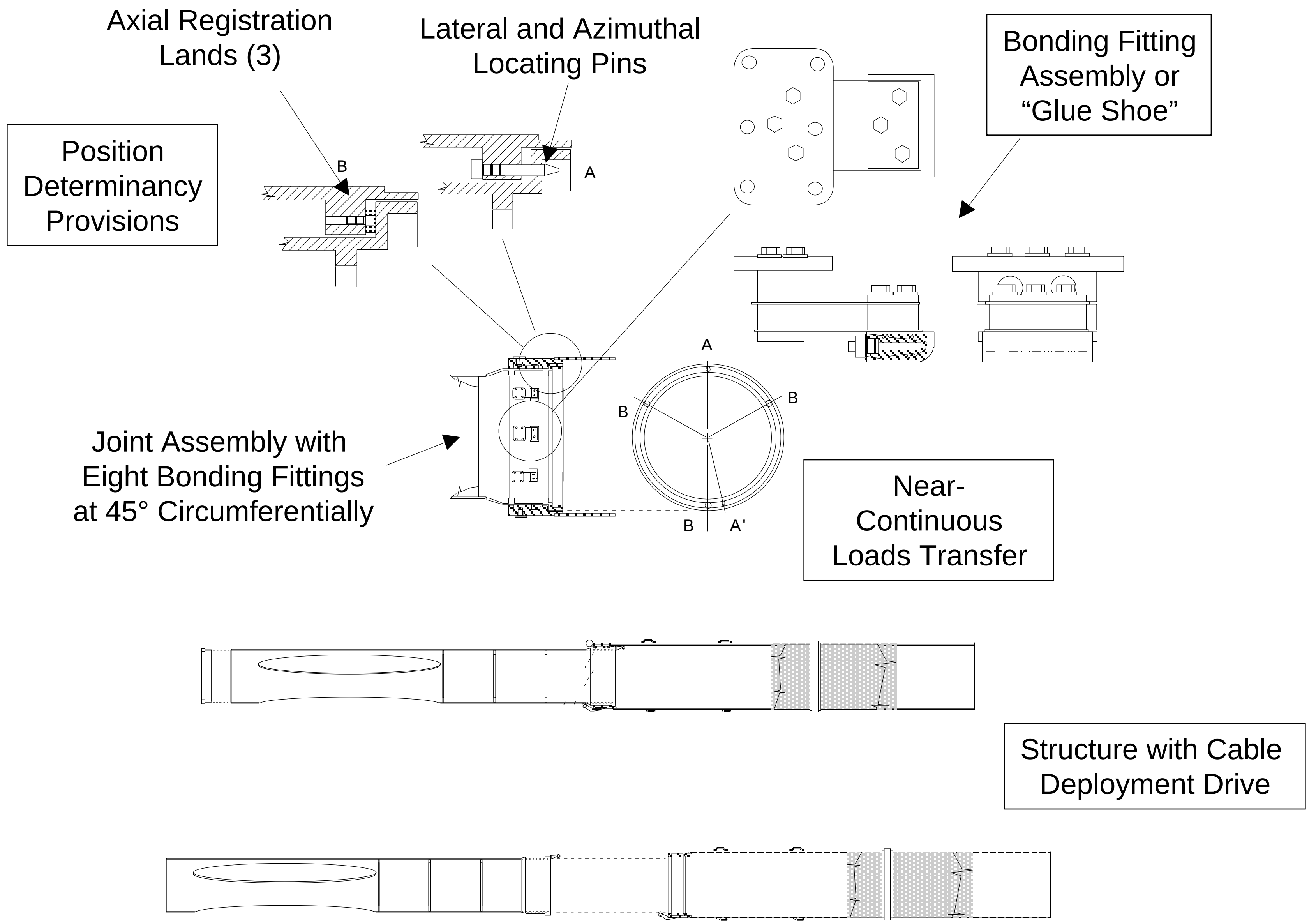
    - Leading to High Variability Bonding Pressure

    - And Therefore Poor Bonding Conditions

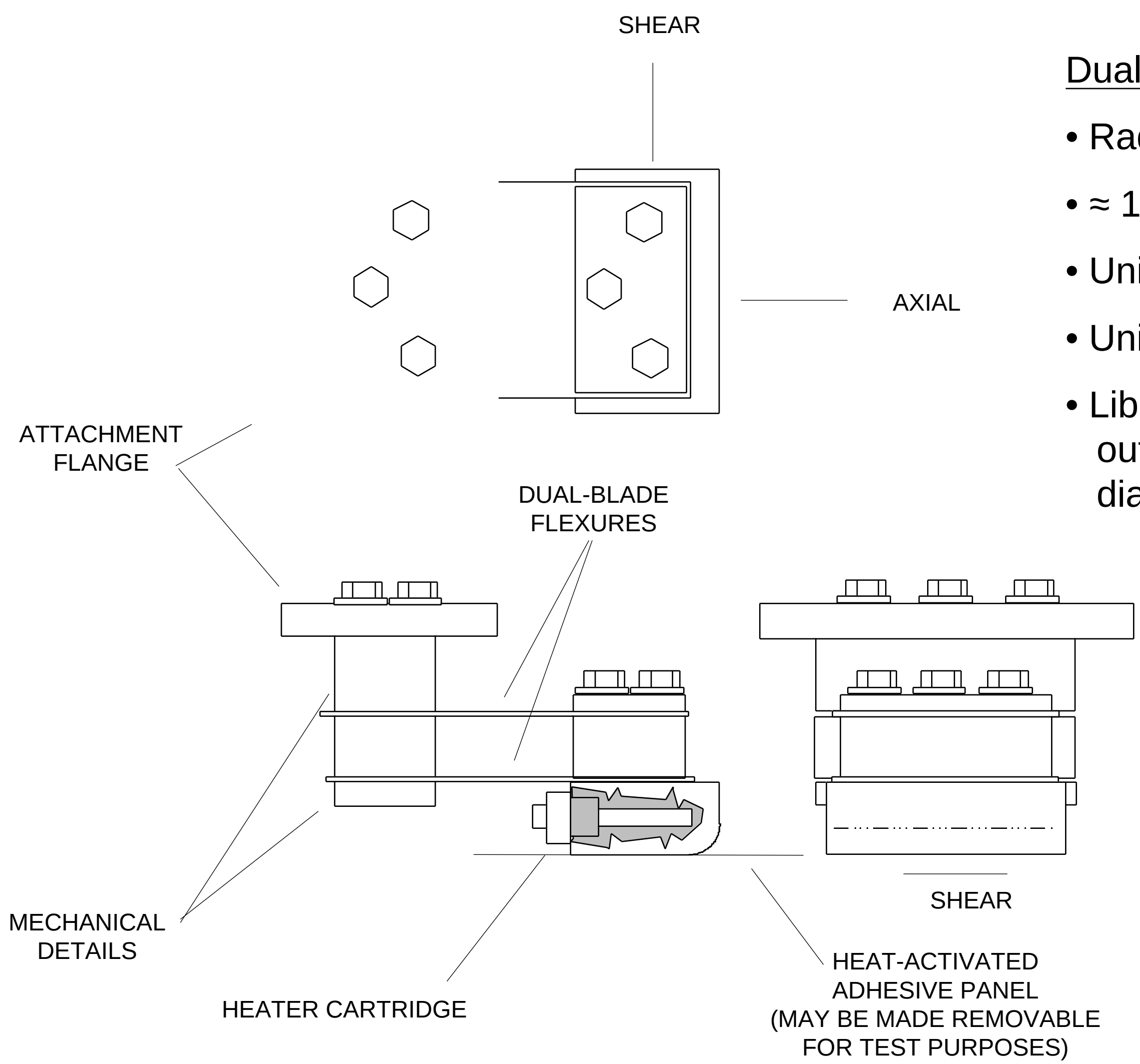
Led to the Broad-Tolerance "Glue-Shoe" Design

- (next chart)

Anatomy of the Tower Joint , and the “Glue Shoe”



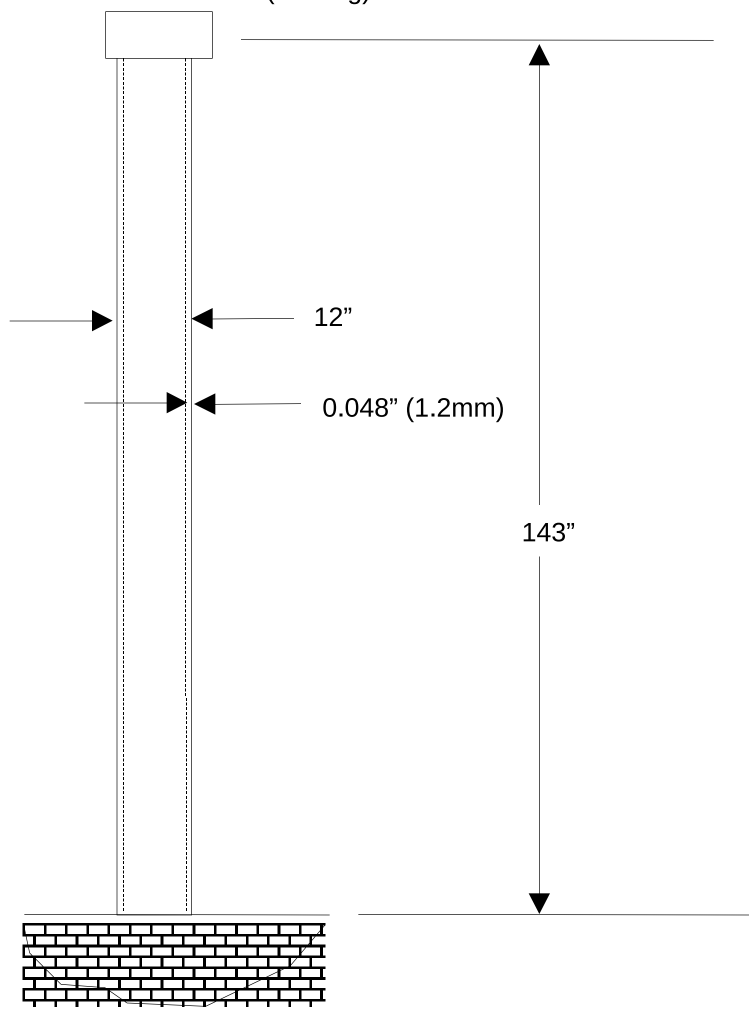
The "Glue Shoe" Concept



Dual Flexures Provide:

- Radial Translation with No Rotation
- ≈ 15 psi clamping pressure for cure
- Uniformity of pressure over shoe area
- Uniform bond-line thickness
- Liberal tolerances between inner and outer joint halves over 'large' diameters

10.8 Hz Jointless Design Provides Stiffness Target



Tower Weight	35 lbs (16 kg)
Bending Material	13
Reinforcements	3
Interface Rings	3
Latch Ass’y	6
Drive System	6
Reserve	4

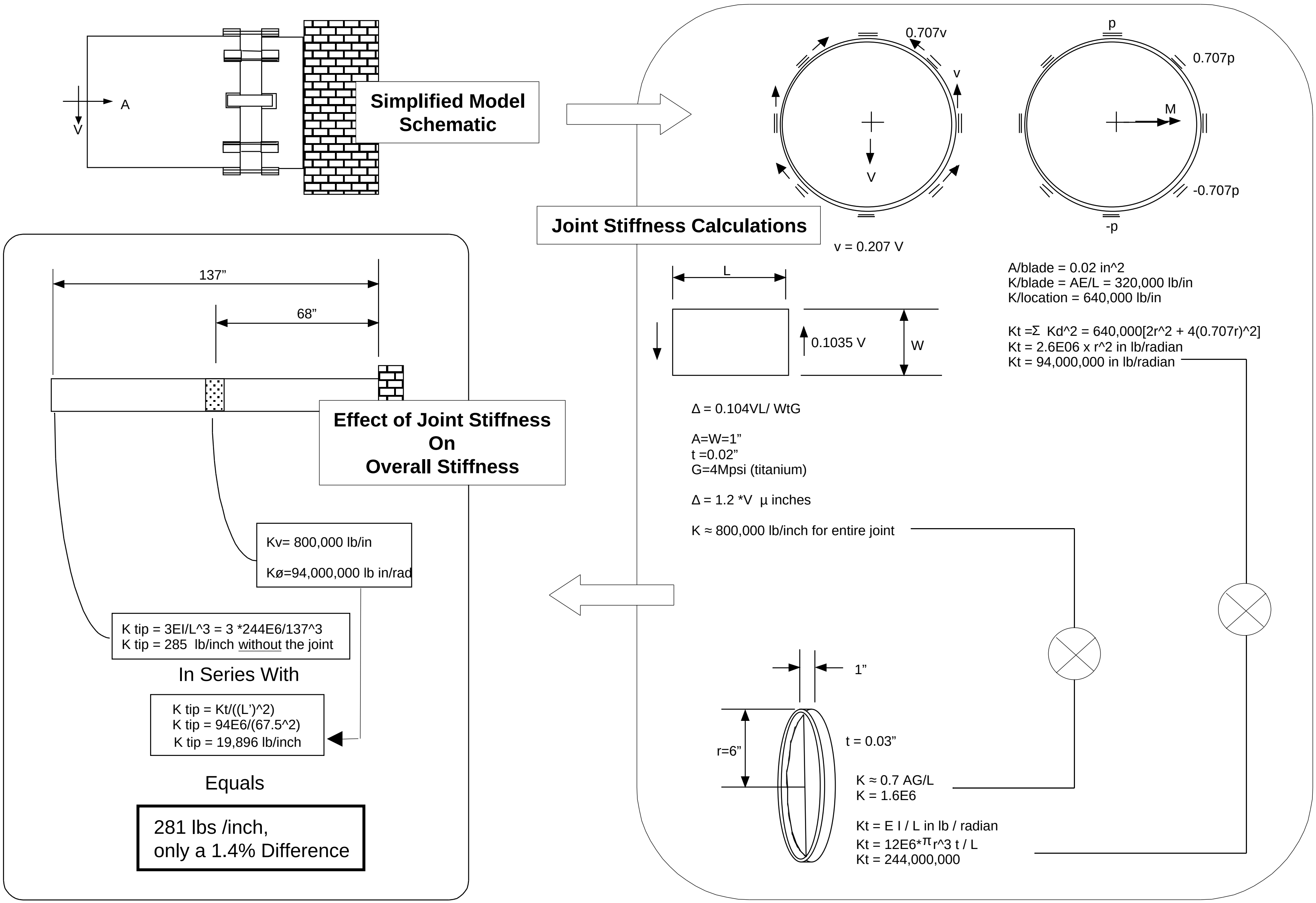
Bending Material Thickness….0.037”
MoI = 25 in^4

End Mass	28.1 lbs
SM	2.5
SM Articulated Drive	17.6 (8 kg)
Tower Effective Mass	8

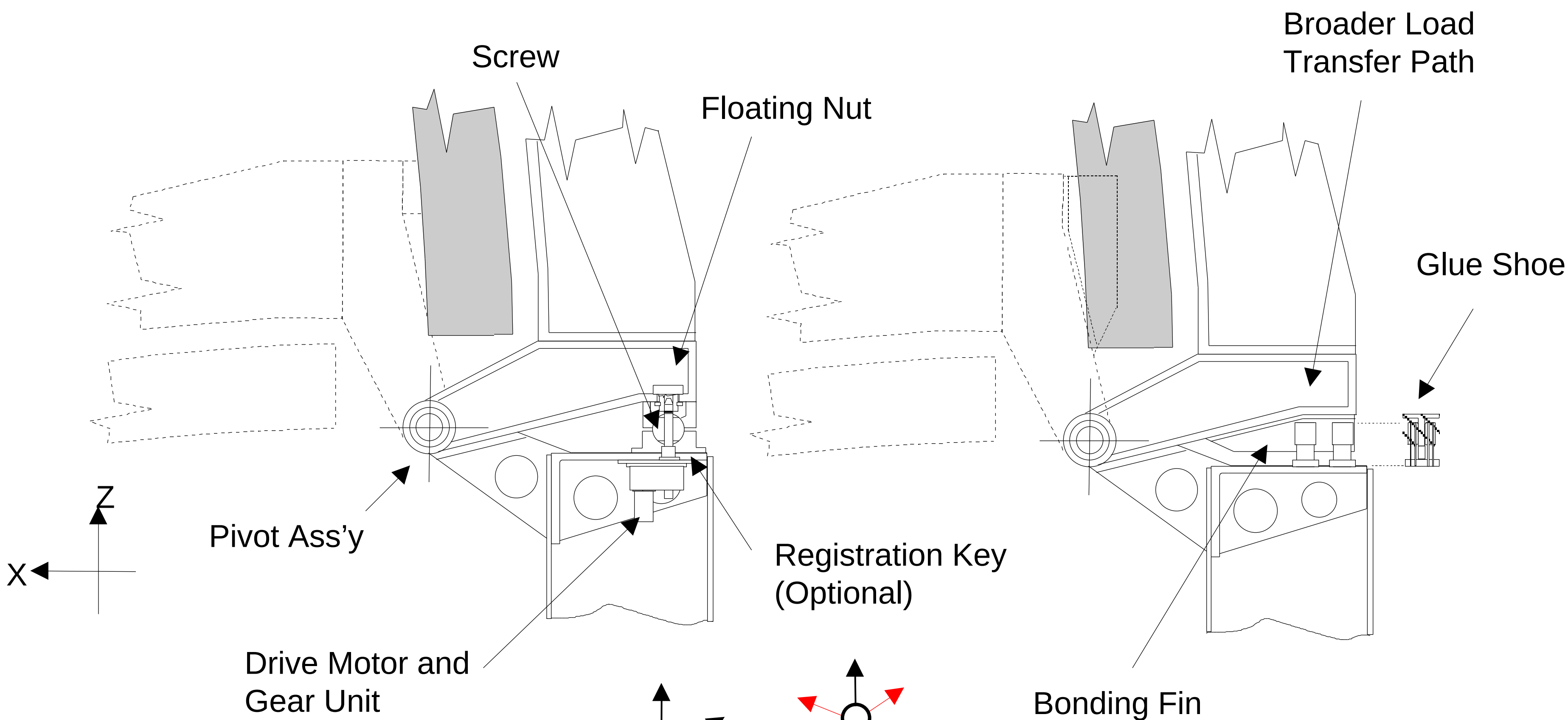
Assumed MoE…………….……12 Mpsi
!’st Mode……………………..10.8 Hz

SOA
Space Optics Applications

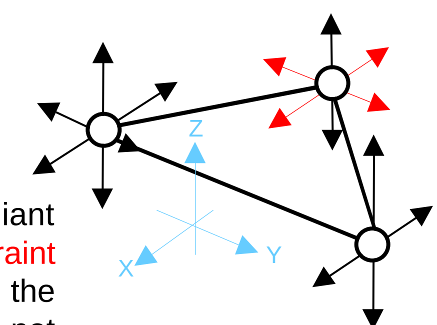
Preliminary Calculations
Confirm Adequacy of Flexure Stiffness



‘Glue Shoe’ Applied to Pivot and Latch Joint



Mechanical Latch



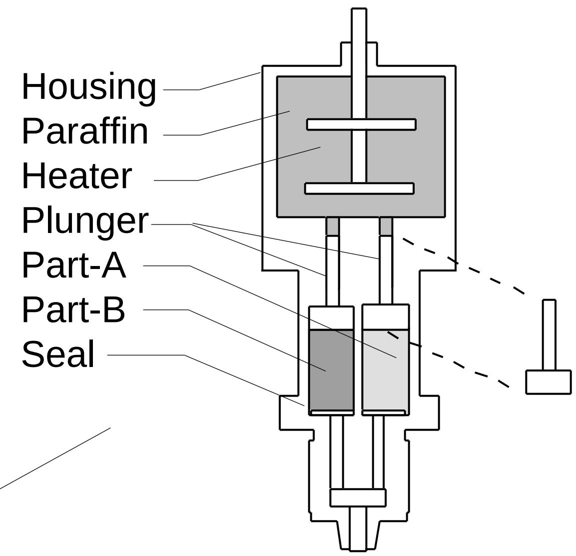
Latch mounting needs to be compliant in X-Y plane to avoid over-constraint conditions in combination with the pivot assembly, otherwise may not fully seat. Details not shown.

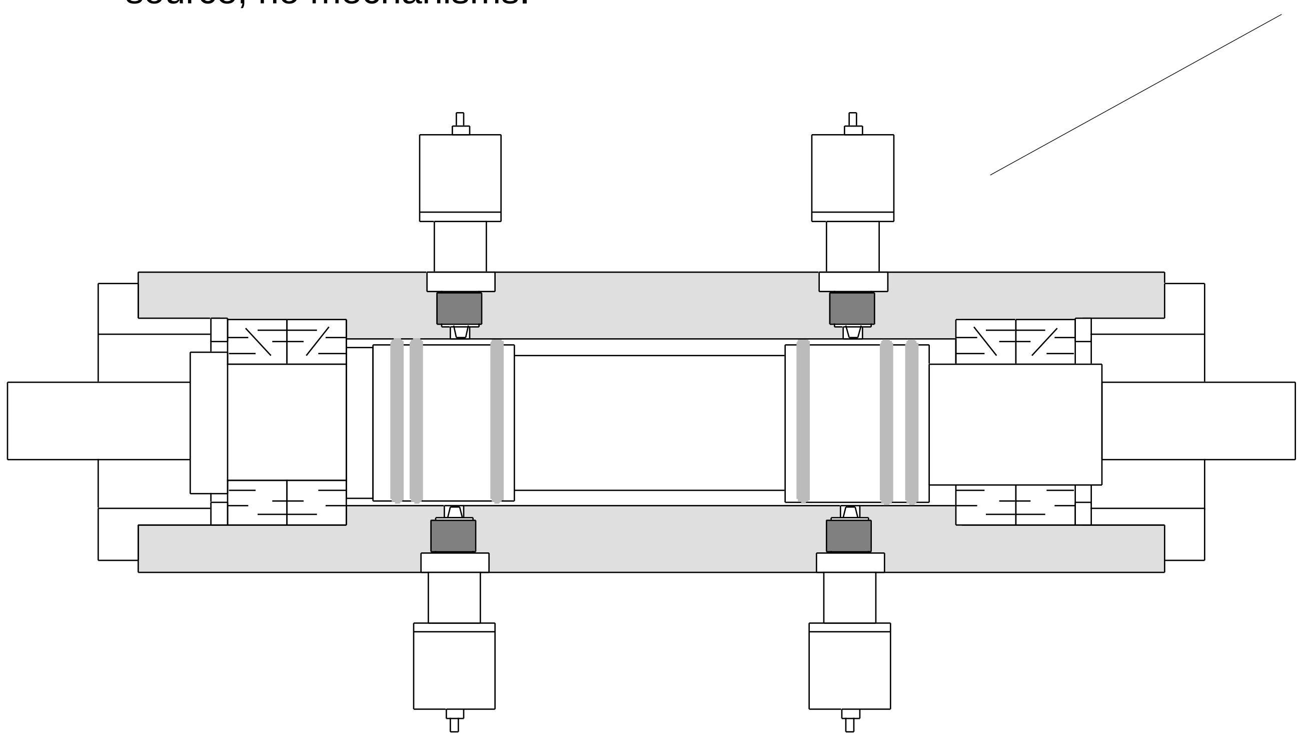
Bonded Connection

Latching over-constraint precluded by use of ‘glue-shoe’. Accommodates large point-to-point tolerances

Rigidizing the Pivot
Sealed Two-Part Adhesive Cartridge

- Largely Tolerance Insensitive
- Unlimited shelf life in vacuum
- Accommodates various adhesive types for different applications
- Built-in mixing chamber
- Simple, automobile radiator thermostat, pressure source, no mechanisms.





Example:

V = 0.75”Ø x 0.75L

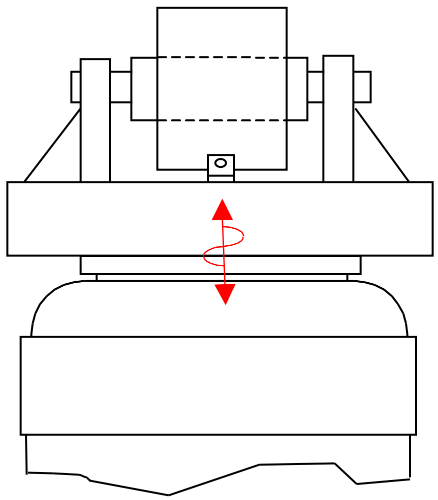
ΔT=100°F

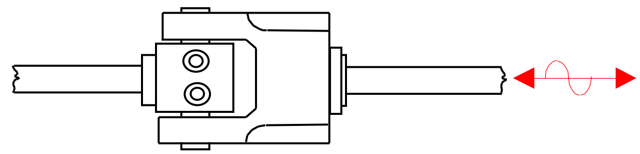
Bore = 0.16”Ø each

Stroke= 0.5 inches

Power= ______

Pivot Rigidizer Experiments





Micro-Dynamics Measurements
Post-Macro Survivability Verification
in 'Strut Tester' after Energizing
the Adhesive Cartridge(s)

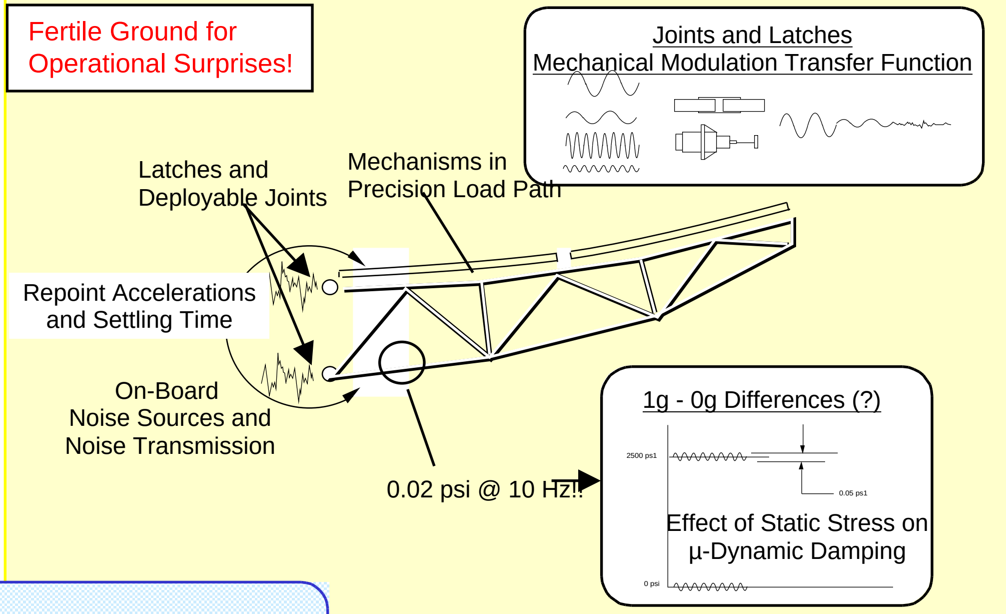
Macro-Dynamics Survivability
Prior to Injecting Adhesive

The “Strut Tester” Briefly…..

Overcoming Superstition with Science in Structures Technology

MicroDynamics and Jitter in Large Deployable Telescopes

- Segment Vibration….10X as critical as SM or LoS Jitter which is SoA re. SBL
- Fractional ‘psi’ stresses…. in Large Structures means Optically Large Displacements
- Mechanisms & Elasticity…Do mechanisms in precision load paths behave as designers expected?
- Testability….will fractional psi strain regime dynamics be the same at 0g as they were at 1g?
- Cryogenics….what dynamics and damping differences between RT and 50K?



MicroDynamics Experiments at Raytheon

In-situ Loading and Boundary Condition Simulations

Damping vs. Amplitude

1g vs. 0g Damping "Δ's"

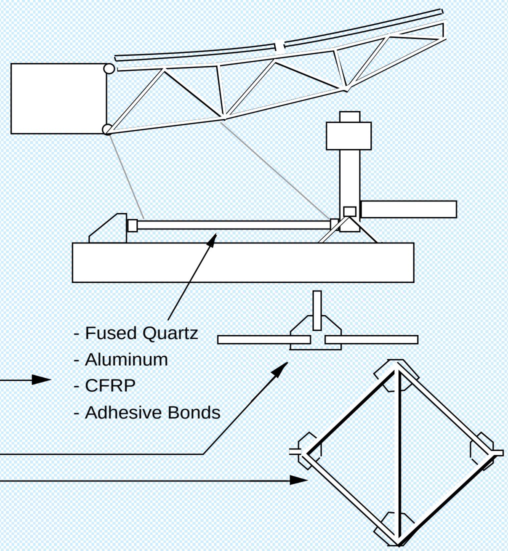
Small Strain Elasticity

Effect of Temperature

Effect of Vacuum (Dryout)

Effectiveness of Damping Augmentation at Nano-Strain Levels, et al

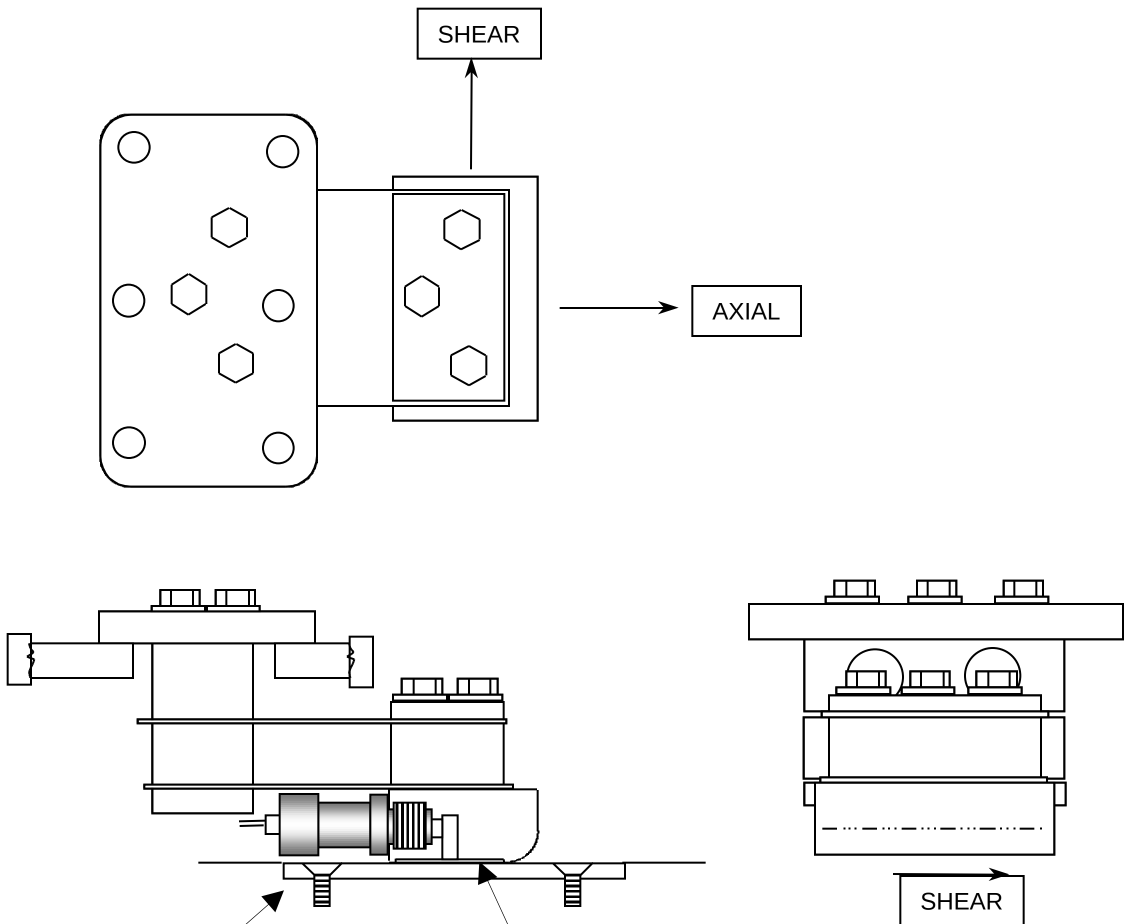
Experiments Include:
- Struts of Different Mat's
- Struts with Joints
- Simple Structures
- Mechanisms and Actuators in Load Path



Raytheon Micro-Dynamics Research

- Laboratory Determination of Component-Level Nano-Dynamics Characteristics
- Incorporate into Structural Models, Early
- Avoid Costly Over-Design
- Avoid More Costly Under-Design!
- Improve Confidence in Designs for the Unprecedented NGST conditions
- Increase Certainty in Cost-to-Launch Estimates
- Increase Certainty in Operational Success

The Adhesive Cartridge Applied to the ‘Glue Shoe’



Removable Platen (Lab Use Only)

0.002” Recess to Define Bond-Line Thickness

Heat-Activated Dry Film and Adhesive Cartridge 'Glue-Shoe', Experiments

As-Cured Strength and Shear Stiffness for Candidate Adherends Over a Range of:

- Cure Temperatures and Durations
- BondlineThickness'
- Cure Pressures
- Pre-Cure Vacuum Durations

Determine range of conditions over which the adhesives can for 'factory-like' or at least dependable bonds. Power Req'ts

Measure Outgassing Quantity and Species

- Part of Overall Material Selection Investigation

Verify low cure products and/or effectiveness of edge closures

µ-Dynamics & µ-Mechanics Behavior:

- Micro-Noise Transmission (MMTF) vs. …..
- Damping vs. Frequency vs. Amplitude
- Damping vs. DC Stress Level ***aka*** 1-g vs. 0-g

Characterize micro- and nano-characteristics of the joints with the Strut Tester

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Engineering Model Joint Assemblies

System Level Applications

end